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ADAPTATION OF FLUX-CORRECTED TRANSPORT ALGORITHMS FOR  
MODELING DUSTY FLOWS(U) NAVAL RESEARCH LAB WASHINGTON  
DC M A FRY ET AL. 20 DEC 83 NRL-MR-5230

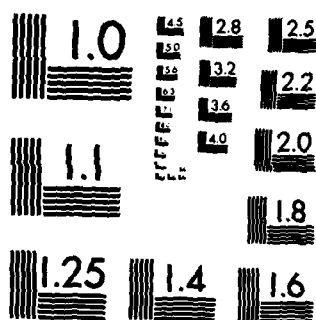
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 5230	2. GOVT ACCESSION NO. <b>AD-A136432</b>	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) <b>ADAPTATION OF FLUX-CORRECTED TRANSPORT ALGORITHMS FOR MODELING DUSTY FLOWS</b>	5. TYPE OF REPORT & PERIOD COVERED Interim report on a continuing NRL problem.	
7. AUTHOR(s) M.A. Fry* and D.L. Book	6. PERFORMING ORG. REPORT NUMBER	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, DC 20375	8. CONTRACT OR GRANT NUMBER(s) N00014-82-C-2229	
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Nuclear Agency Washington, DC 20305	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62715H; 44-0578-0-3	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	12. REPORT DATE December 20, 1983	
	13. NUMBER OF PAGES 23	
	15. SECURITY CLASS. (of this report) <b>UNCLASSIFIED</b>	
	16. DECLASSIFICATION/DOWNGRADING SCHEDULE	
18. DISTRIBUTION STATEMENT (of this Report)  Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
19. SUPPLEMENTARY NOTES *Present address: Science Applications, Inc., McLean, VA 22102 This work was supported by the Defense Nuclear Agency under Subtask N99QAXAH, work unit 00061, work unit title "Cloud Calculations," and under Subtask Y99QAXSG, work unit 00057, work unit title "Airblast Calculations."		
20. KEY WORDS (Continue on reverse side if necessary and identify by block number)  Flux-corrected transport      Airblast Finite-difference algorithms      Height-of-burst		
21. ABSTRACT (Continue on reverse side if necessary and identify by block number) Blast wave phenomena include reactive and two phase flows resulting from the motion of chemical explosion products. When the blast wave interacts with structural surfaces (external discontinuities), multiple reflections and refractions occur from both external and internal discontinuities. The most recent version of the Flux-Corrected Transport (FCT) convective- equation solver has been used both in one and two dimensions to simulate chemical explosive blast waves reflecting from planar structures for yields ranging from 8 lbs to 600 tons. ~) ~)		

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20. ABSTRACT (Continued)

cont > One can relate the strength of the second reflected peak to the sharpness of the contact discontinuity, and thus measure the capability to predict all the salient features of the blast wave. The flow patterns obtained reveal four different vortices, two forward and two reversed. Their effect on the motion of tracer particles has been studied in order to determine the motion of (1) HE detonation products and (2) dust scoured up from the ground.



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## ADAPTATION OF FLUX-CORRECTED TRANSPORT ALGORITHMS FOR MODELING DUSTY FLOWS

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### INTRODUCTION

In this paper we describe a series of calculations carried out as part of an ongoing effort aimed at studying blast wave diffraction effects in air. The phenomena of chief interest to us include velocity fields, particularly those associated with the toruses (both forward and reverse) in the neighborhood of the rising fireball, and the distribution of dust lifted off the ground by the winds and the structure of the cloud at the time of stabilization. We are interested in studying the nature of the gas-dynamic discontinuities which appear, the vortices (both forward and reverse), and how the dust content of the air affects the evolution of the blast wave.

The technique we have employed for this purpose is numerical modeling. One- and two-fluid hydrocodes based on the Flux-Corrected Transport (FCT)<sup>1</sup> shock-capturing techniques have been used to simulate airblast phenomena in one and two dimensions. FCT refers to a class of state-of-the-art fluid computational algorithms developed at NRL in the course of the past ten years with supersonic gas-dynamic applications expressly in mind. We have concentrated on modeling the "Direct Course" event, an experiment to be fielded shortly by the Defense Agency: a 600-ton ammonium nitrate + fuel oil (ANFO) charge is detonated at a height of burst (HOB) of 166 ft. The results are most conveniently exhibited in terms of velocity vector plots and tracer particle trajectories. Examples of these are presented to illustrate our results and conclusions.

The plan of the paper is as follows: In the next section we discuss our numerical techniques and validation procedures. In Section 3 we describe the 600-ton 2D HOB calculations. In Section 4 we summarize our conclusions and discuss their domain of validity.

Manuscript approved September 13, 1983.

## NUMERICAL TREATMENT

As described by Boris and Book<sup>1</sup>, FCT is a finite-difference technique for solving the fluid equations in problems where sharp discontinuities arise (e.g., shocks, slip surfaces and contact surfaces). It modifies the linear properties of a second- (or higher-) order algorithm by adding a diffusion term during convective transport, and then subtracting it out "almost everywhere" in the antidiffusion phase of each time step. The residual diffusion is just large enough to prevent dispersive ripples from arising at the discontinuity, thus ensuring that all physically positive conserved quantities remain positive. FCT captures shocks accurately over a wide range of parameters. No information about the number or nature of the surfaces of discontinuity need be provided prior to initiating the calculation.

The FCT routine used in the present calculations, called JPBFACT (an advanced version of ETBFCT<sup>2</sup>), consists of a flexible, general transport module which solves 1-D fluid equations in Cartesian, cylindrical, or spherical geometry. It provides a finite-difference approximation to conservation laws in the general form:

$$\frac{\partial}{\partial t} \int_{\delta V(t)} \phi dV = - \int_{\delta A(t)} \phi (\underline{u} - \underline{u}_g) \cdot d\underline{A} + \int_{\delta A(t)} \tau dA, \quad (1)$$

where  $\phi$  represents the mass, momentum, energy or species mass density in cell  $\delta V(t)$ ,  $\underline{u}$  and  $\underline{u}_g$  represent the fluid and grid velocities, respectively, and  $\tau$  represents the pressure/work terms. This formulation allows the grid to slide with respect to the fluid without introducing any additional numerical diffusion. Thus, knowing where the features of greatest interest are located, one can concentrate fine zones where they will resolve these features most effectively as the system evolves.

The same transport routine was employed for both coordinate directions in the 2D r-z code (called FAST2D) via timestep splitting. A Jones-Wilkins-Lee (JWL) equation of state (EOS) was used for the detonation products and a real-air EOS was used outside the HE-air interface<sup>3</sup>. The routine was written in the form of a table lookup, using interpolation with logarithms to the base 16 computed by means



of logical shifts<sup>4</sup>. By thus taking account of the architecture of the machine (in these calculations, a 32-bit-word two-pipe Texas Instruments ASC) it was possible to generate very efficient vector code, decreasing the time required for EOS calculations to a small fraction of that required for the hydro. The EOS specifies pressure as a function of density and internal energy. In mixed cells the combined pressure was calculated according to Dalton's law.

The initial conditions were taken to be the self-similar flow field used by Kuhl, et al.<sup>3</sup>, corresponding to a spherical Chapman-Jouquet detonation at the time the detonation wave reaches the charge radius (Fig. 1). This was propagated with the 1D spherical code until the detonation front attained a radius just smaller than the HOB, at which time the solution was laid down on the 2D mesh (Fig. 2).

The boundary conditions were chosen to enforce perfect reflection on the ground and on the axis of symmetry  $[(d\phi/dn)_{bc} = 0, \text{ where } \phi = \rho, p, v^t, \text{ and } v_{bc}^n = 0]$ , where "t" and "n" denote tangential and normal components, respectively, and outflow on the outer and the top boundaries  $[(d\phi/dn)_{bc} = 0, \text{ where } \phi = \rho, p, v^t, v^n]$ .

For the 2D calculations the mesh was typically 200 x 100. Fixed gridding was used to minimize numerical errors. The zone sizes were 2.1 m x 2.1 m, respectively. For the late-time calculations, a fixed mesh with 100 zones in the radial and 200 zones in the vertical direction was used, with all cells of dimension 4.2 m x 4.2 m.

To study the motion of dust particles in the flow field generated by the calculation, the simplest model describes dusty air as a single phase with density and adiabatic index chosen appropriately. This approach ignores the properties associated with the particulate structure of the dust and the process of scouring by which the dust enters the air. A more realistic picture results if we treat the dust as a distinct phase, described by equations of mass, momentum and energy conservation, as has been done in one dimension by Miura and Glass<sup>5</sup>. The dust equations are coupled to those describing the air through drag and heat transfer terms.

It has been pointed out by Ruhl<sup>6</sup> that in such a treatment a dust particle tends to become entrained in the prevailing flow over a distance  $\sim 10^3$  particle diameters. Thus a one-phase description is satisfactory whenever particle sizes are at least a thousand times smaller than the smallest length scale in the hydrodynamics. For the present calculation, this scale is roughly 1 m, so particles smaller than 1 mm can be regarded as totally entrained.

When the mass density of the dust component is small compared with air (or HE product) density, a further simplification is possible. Entrained dust particles can be followed by passive advection. That is, the wind fields  $u_x$ ,  $u_y$  are taken from a dust-free hydrodynamics calculation, and dust is advected in these fields according to

$$\frac{dx}{dt} = u_x, \quad \frac{dy}{dt} = u_y. \quad (2)$$

In this approximation we ignore the effect of the momentum and energy transfer on the air phase. The same approximation can be used for larger (nonentrained) particles also, provided we include inertia and drag by using the force law

$$m \frac{d\mathbf{y}}{dt} = -mg\mathbf{e}_z + D(\mathbf{y} - \mathbf{y}) , \quad (3)$$

where  $\mathbf{y}$  is the particle velocity,  $g$  is the acceleration due to gravity, and  $D$  is the empirical drag coefficient employed by Miura and Glass<sup>5</sup>.

Equations (2) and (3) apply best in the limits of extremely small and extremely large particles, respectively. Although they restrict the scope of the calculation (by requiring the dust content to be small), they have the computational advantage of allowing us to obtain time-dependent dust distributions for many different choices of dust size spectrum and initial distribution from a single hydrodynamics calculation.

## 600-TON ANFO EXPLOSION AT 166 FT

The yield and HOB (600 tons and 166 ft, respectively) in the calculation were chosen to equal the values used in the Defense Nuclear Agency Direct Course experiment, which we are simulating. The Chapman-Jouguet parameters used to initialize the spherical free-field calculation were taken to be those for the  $\text{NH}_4\text{NO}_3$ -fuel oil (ANFO) mixture used as the explosive.

Figs. 3(a)-(c) show the contours of HE density and internal energy per unit mass and the velocity arrow plot at  $t=0$ , just before the reflection at ground zero occurs. Figs. 3(d)-(f) show the corresponding plots 54 ms later, while Figs. 3(g)-(i) show them after 245 ms. Note the reflected shock proceeding upward, reflecting again off the fireball, and propagating back in a downward and outward direction. The interaction of this shock with the radially inward flow near the ground generates the reverse vortex, which is clearly seen in Fig. 3(i). Note also the positive vortex forming near the top of the grid in the same plot. The latter results when the upward-propagating reflected shock interacts with the radially outward flow near the top of the fireball; it is not produced by the buoyant rise of the fireball, which at these early times has scarcely begun.

To look at the evolution of the fireball at late times, we reinitialized on a larger, coarser grid, representing a cylinder 400 m in radius and 800 m high. The first 300 cycles approximately reproduce the early-time results. The spherical shock breaks away and leaves the mesh. The flows remaining on the grid are now subsonic everywhere. Then the fireball begins to rise and the subsequent development is due to the combination of buoyant rise and the action of the vortices set up by the early shocks.

Figure 4a, which shows the trajectories of passively advected tracer particles over the time interval 1.8 sec to 3.97 sec, displays the vortices very clearly. Fig. 4b shows the particle paths for the time interval 3.97 sec to 7.34 sec. Notice that there are four vortices visible in the plot: two positive and two reversed. The additional small vortices are apparently a consequence of entrainment by the major ones. As far as we know, their existence has not been noted previously.

It is clear that the major qualitative features persist longest in the velocity plots. This is not surprising, as the circulation patterns represented by the vortices have essentially infinite lifetimes in the absence of viscosity. We have run out to stabilization (not shown here) and have found that these features persist in the velocity plots to the very end. At all times  $t > 0$  the peak flow velocity in the HE case exceeds that in the comparable point source solution. This is a reflection of the fact that the Chapman-Jouguet solution at a radius of 10 m has a pressure peak of 52 kbar, vs 3 kbar for the Sedov solution at the same radius. This means that the former starts out with much more violent motion, i.e., fluid velocities an order of magnitude larger. All in all, in many respects the HE case does not closely resemble a point source.

#### CONCLUSIONS

We have described a numerical simulation of the Direct Course Event. The code, gridding, and method of solution are the same in the two calculations. The following conclusions appear to be among the most important.

- (i) The flow establishes a pattern of four vortices, two forward and two reversed, instead of one of each.
- (ii) The upper vortex forms first, followed by the reverse vortex near the axis of symmetry and the ground. Adjacent HE products begin to be entrained into a positive vortex over a longer period of time, several seconds.
- (iii) Once picked up (scoured) off the ground, dust is efficiently transported upward by the reverse vortex farther from the axis.

Phenomena neglected in the present model (e.g., terrain, conditions in the boundary layer, turbulence, humidity, etc.) are unlikely to alter the above conclusions, which mainly depend on the characteristics of the solutions in the interior of the mesh and over long periods of time. Further study of the tracer particle motions we have calculated is likely to be illuminating, particularly when we begin to consider the evolution of various initial configurations as a function of particle size. In closing, it is appropriate to emphasize the far-reaching significance of the role played by the HE-air interface in the dynamics of both airblast and cloud rise phenomena, and the importance for numerical simulation of correctly treating this interface.

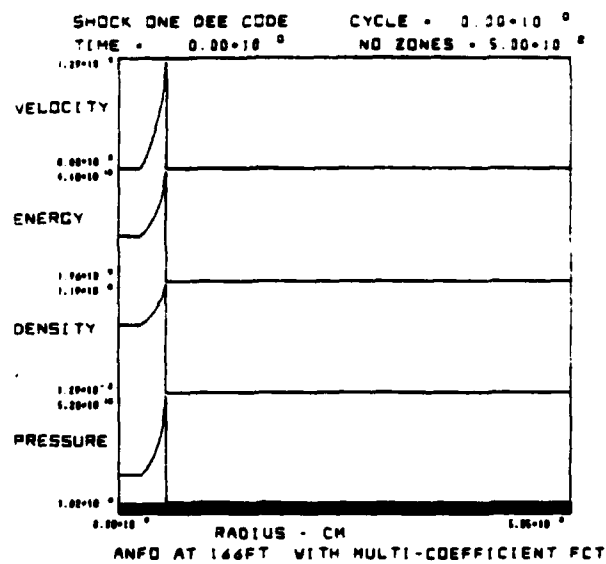


Figure 1

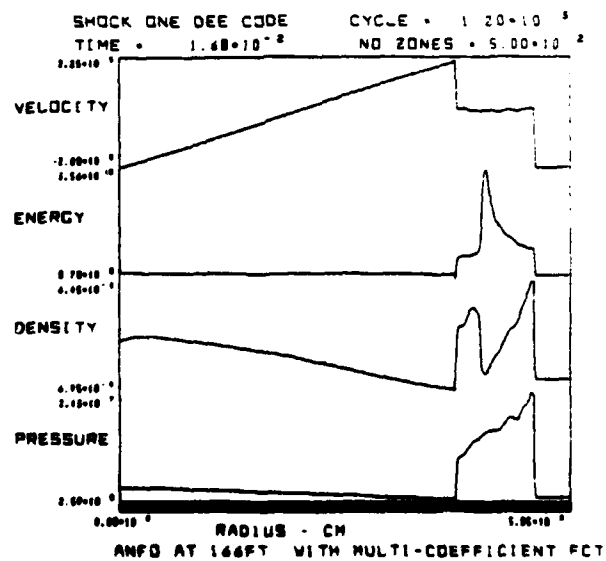


Figure 2

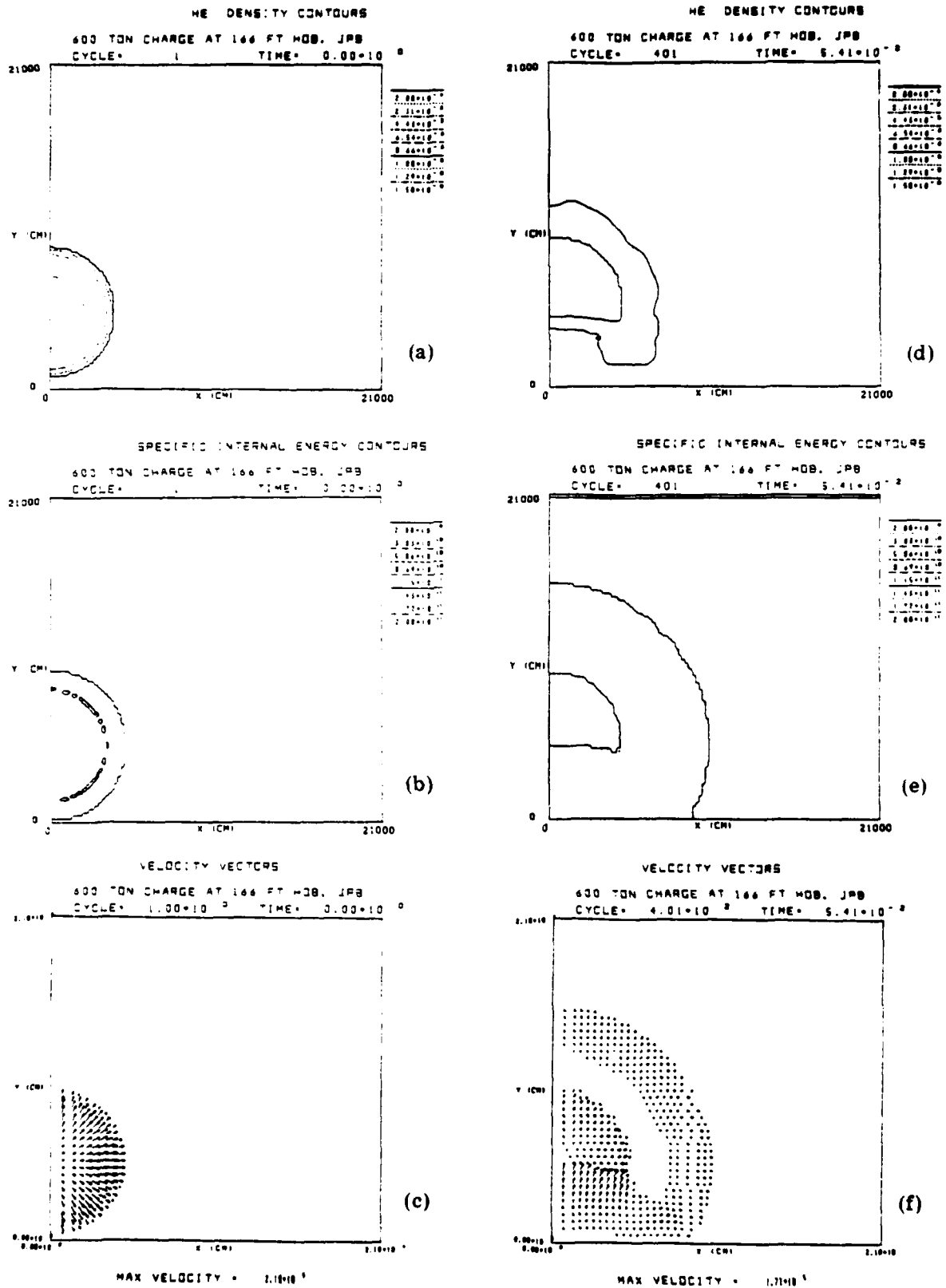


Figure 3

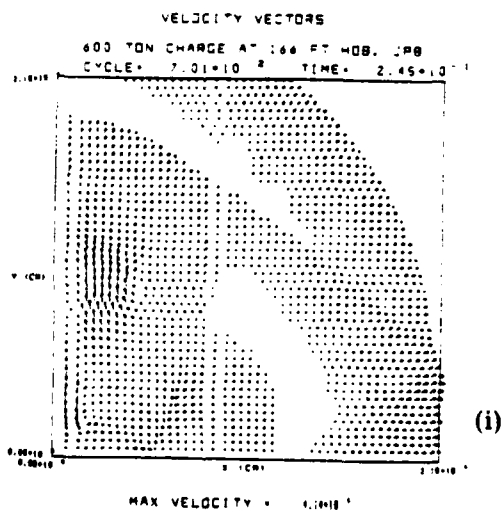
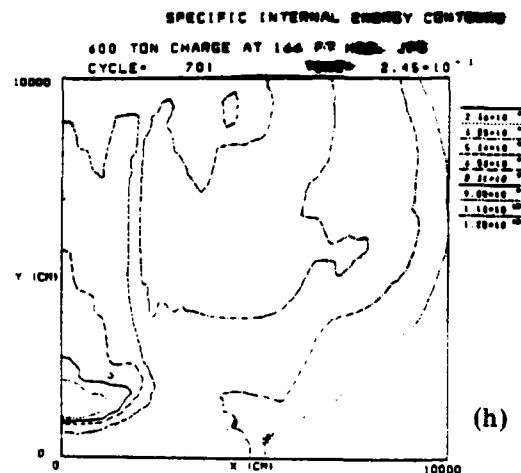
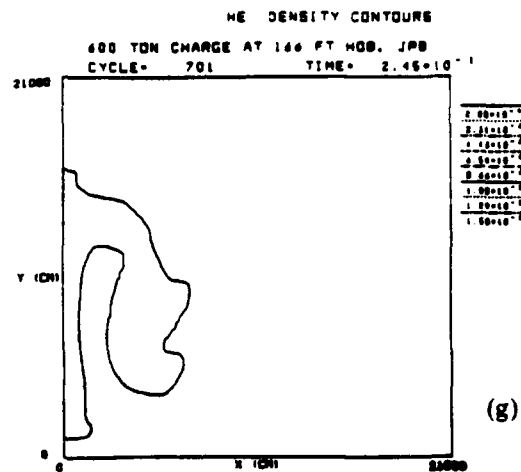
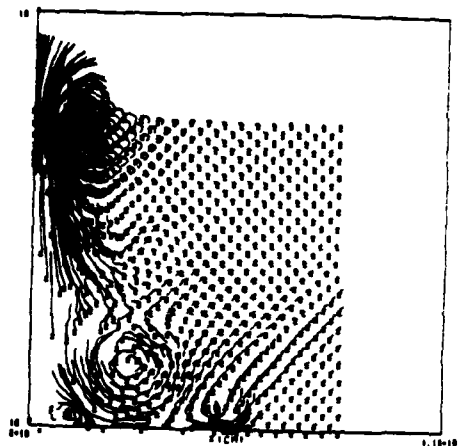


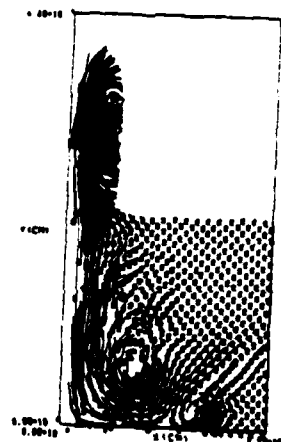
Figure 3 (Cont'd)

PARTICLE PATH PLOT  
400 TON DIRECT COURSE



(a)

PARTICLE PATH PLOT  
400 TON DIRECT COURSE



(b)

Figure 4



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## ACKNOWLEDGMENT

This work was supported by the Defense Nuclear Agency under Subtask N99QAXAH/MISSILE SYSTEMS/X-Ray Hardness, Work Unit # 00061, Work Unit Title "Cloud Calculations," and under Subtask Y99QAXSG/AIRBLAST AND THERMAL PREDICTIONS Work Unit #00057, Work Unit Title "Airblast Calculations."

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